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Light Penetration Properties of Visible and NIR Radiation in Tomatoes Applied to Non-Destructive Quality Assessment †

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Abstract: Tomato is an important food product for which the development of non-destructive quality assessment methods is of great interest. Using visible and near-infrared (NIR) spectroscopy, the sugar content, acidity and even taste can be estimated through the use of chemometric methods (e.g., partial least squares regression). In the case of reflection spectra, which are the common modality for imaging spectroscopy, the question arises regarding how much of the interior of the tomato contributes to the measured spectra. An experiment was performed with tomatoes of four different types: beef tomato, classic round tomato, cocktail tomato, and snack tomato. The tomatoes were sliced at different thicknesses and imaged on a 98% reflective white background and a 4% reflective black background. Spectral images were acquired with VNIR (400–1000 nm) and NIR (900–1700 nm) imaging spectrographs. The difference between the spectra with a white and black background was used to determine the relationship between the wavelength and the light penetration depth. The results show that at wavelengths between 600 and 1100 nm, light penetrates the tomatoes up to a distance of 20 mm. The relation more or less follows the law of Lambert–Beer. This relation was the same for all four types of tomatoes. These results help the interpretation of chemometric models based on reflection (imaging) spectroscopy.

Keywords: light penetration; NIR radiation; tomato; quality assessment; non-destructive

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1. Introduction

The ripeness of a tomato is very important. A tomato that is ripened before picking has a better flavor and overall quality compared to tomatoes ripened after picking. Lycopene is a carotenoid pigment related to ripening. It is responsible for the red color of the tomato [1]. Sugars in tomatoes are closely related to fruit quality and yield, but also in fruit set, ripening, composition, and growth [2]. Sugars, mainly fructose and glucose, account for about 65% of the soluble solids of ripe tomatoes [3]. The soluble solids value expressed in Brix is determined by the variety, method of cultivation, and environmental conditions. A refractometer can be used to measure the percentage of solids in juice. This method is destructive, labor intensive, and expensive. As an alternate, visible and NIR spectroscopy can be used as a non-destructive quality measurement method for features such as sugar content, acidity, and taste. Imaging spectroscopy, also known as hyperspectral imaging [4], is a special mode of spectroscopy that generates a spatial map of spectral variation [5]. Each vector in the array represents the reflection spectrum at the specific pixel location.

The interaction between light and the tomato is a complicated phenomenon; it involves both absorption and scattering [6]. Photons scatter multiple times before being absorbed or exited from the fruit. The absorption of light is primarily related to chemical components such as sugar [7]. The scattering of light is influenced by physical and structural features, such as particle size, density, and cellular structure. Since absorption and scattering are intertwined, it is challenging to relate the spectra to the concentration of the compounds. The Lambert–Beer law ascribes the absorption of light with the properties of the material it passes through. The Lambert–Beer law states that the intensity of the electromagnetic wave decreases exponentially from the surface of a sample, for homogeneous media:

$$I/I_0 = e^{-\mu d} \tag{1}$$

where I is the transmitted light, I_0 is the incident light, μ is the attenuation coefficient, and d is the thickness of the sample. There is a growing interest in using imaging spectroscopy in reflection mode to estimate the quality and attributes of food products. The question arises regarding how much of the interior of a fruit contributes to the measured spectra. In this paper, we answer this question by investigating light penetration in four different types of tomatoes. Knowing the relation between light absorption and penetration depth provides insight into the contribution of internal compounds to the measured spectra.

2. Materials and Methods

Four types of tomatoes (beef tomato, classic round tomato, cocktail tomato, and snack tomato) were imaged with an imaging spectrograph, sliced at different thicknesses on a black and a white surface. When light penetrates through the slice onto the surface, the white surface reflects the light resulting in a higher measured reflectance compared to the light-absorbing black surface. When the tomato slice has a thickness for which all light is absorbed before reaching the background, there will be no difference between the measured reflectance on both surface colors. This idea is visualized in Figure 1.

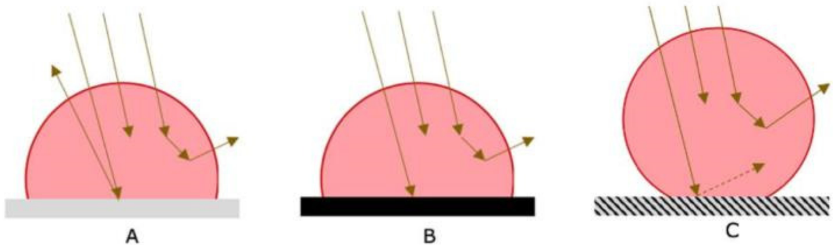

Figure 1. Visualization if (**A**,**B**) the transmitted light influences the reflected light for the different colored backgrounds, and if not (**C**). The striped surface for C indicates a similar result for both background colors.

A white Teflon (PTFE) plate that reflects 98% of the incoming light between 300 and 1900 nm was used as a white background. A black nylon polyurethane-coated fabric that reflects 4% of light between the wavelengths 400 to 2400 nm was used as a black background. Two spectral line scan cameras, Specim FX10 and Specim FX17, were used for the spectral measurements. The spectral range for the Specim FX10 camera is 400 to 1000 nm, with a resolution of 5.5 nm. The spatial resolution is 1024 pixels. The exposure time was 6 ms. The spectral range for the Specim FX17 camera is 900 to 1700 nm, with a spectral resolution of 8 nm and the spatial resolution is 640 pixels (Specim, 2020b). The exposure time was 3 ms. Scan speed was adjusted to obtain square pixels. Two 150 W Dolan Jenner PL900 tungsten halogen lamps with glass fiber optic line arrays of 0.5 mm × 152.4 mm and a quartz rod lens formed a line-shaped beam of light on the samples. A 1000 W halogen tube was used for illumination in the infrared spectrum; the tube operated at 75% of the nominal voltage (170 V), which resulted in an output of 570 W. An exponential model was fitted on the data of the first sample and validated on the second sample of each tomato type for the wavelengths 500, 700, 900, 1100, 1300, and 1500 nm.

3. Results

Between the thickness of 0 to 20 mm and wavelengths 600 to 1100 nm, a definite difference in reflectance between the black and white background was observed. For the other combinations of thicknesses and wavelengths, there was not a clear reflectance difference between the two different backgrounds (Figure 2). The reflectance values showed similar values for the different types of tomatoes. Exponential models were fitted for the six wavelengths. Figure 3 shows the data points of both samples and the fitted model on the first sample for the classic tomato at 500 and 900 nm. From this figure, the exponential relationship can clearly be seen for 900 nm. For wavelengths between 700 and 1300 nm and for the beef, classic, and cocktail tomatoes, the models showed comparable results. At 500 nm, for each type of tomato, the relation is more linear.

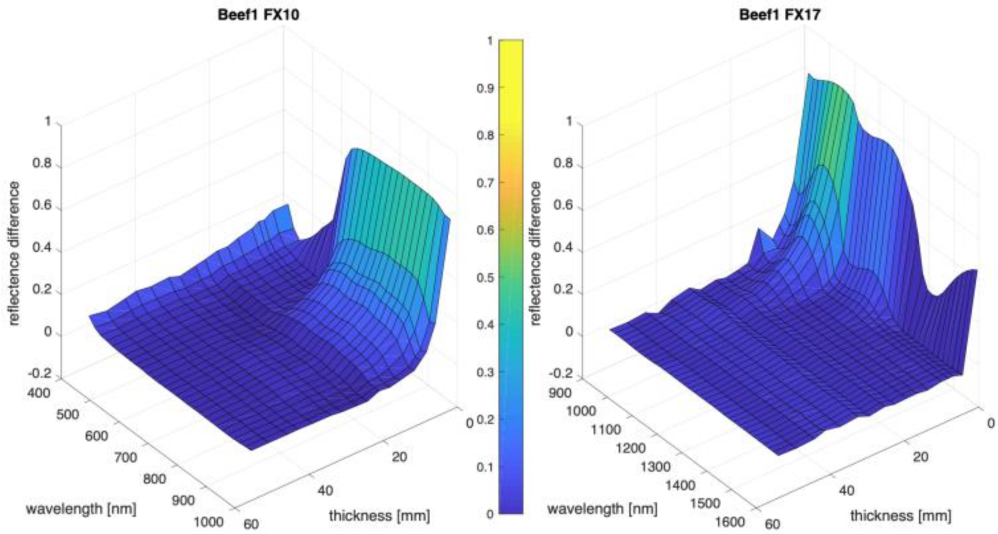

Figure 2. Three-dimensional plots of thickness, wavelength, and reflectance difference for beef tomato sample 1.

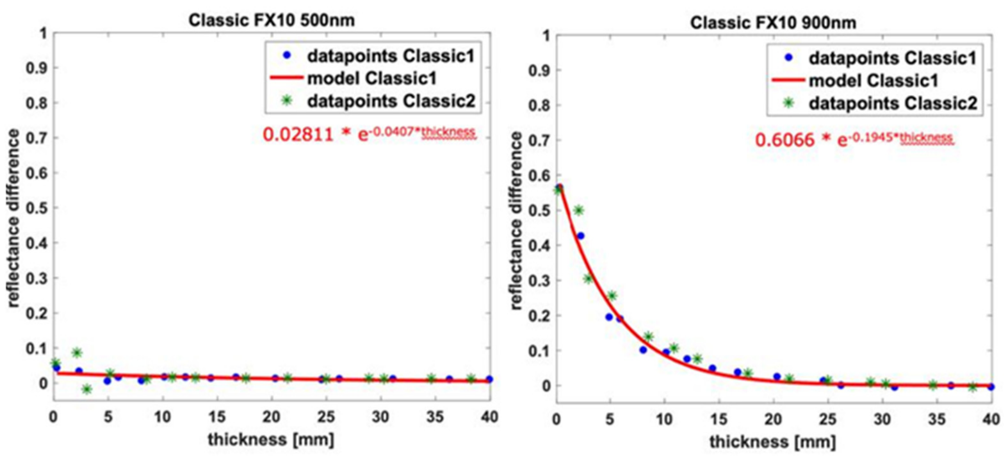

Figure 3. The plot of the model for the classic tomato and data points of the first and second samples for 500 and 900 nm.

Since the models were based on the data of the first samples (training data), the R2 for this data should be close to one. This was the case for most models, but not for classic 500 nm, cocktail 500 nm, snack 500 nm, and 1500 nm. The R2 on the second sample (validation data) was below 0.75 for the beef 500 nm and 1500 nm, classic and cocktail 1500 nm, and all of the other snack models.

4. Discussion

When looking at the 3D surface plots of the thickness, wavelengths, and reflectance difference for the different types and samples of the tomatoes, only combinations of a thickness between 0 to 20 mm and a wavelength between 600 to 1100 nm showed an evident increase in the signal, proving that for these wavelengths the interior of the tomato contributes to the reflection spectra. For the other combinations of thickness and wavelength, there was no evident surface increase visible. This suggests that for all wavelengths, an interior deeper than 20 mm does not contribute to the measured spectra. For the wavelengths 400 to 600 and 1100 to 1700, the interior seemed to barely affect the result. The models for the snack tomato all performed badly, most likely because of the very few data points available. The models for the wavelength 500 nm did also not reach the minimum R2 of 0.75. This might have been a result of the uncertainty of the sensor at the beginning of the range due to the lack of irradiance of the light source in this wavelength. From the literature, it is known that temperature has a major impact on optical properties in the NIR spectrum of the sample. In this research, the temperature was not taken into account; future research is required to evaluate the effect of temperature on the measured spectra.

5. Conclusions

The interior of a tomato contributes to the result of reflection imaging spectroscopy for a maximum tomato thickness of 20 mm when the wavelength of the measurements lies between 600 to 1100 nm. An exponential relation was visible between the decreasing thickness of the tomato and the increasing reflectance. This is in accordance with the Lambert–Beer law, although this law is only defined for homogeneous material. Outside the wavelength range 600 to 1100 nm or when the tomato thickness was larger than 20 mm, the interior did not significantly influence the result of reflection imaging spectroscopy. The tomato type also did not influence the light penetration.

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